MAPPING ANGKOR WITH AIRSAR/TOPSAR DATA

Anthony Freeman[1], Scott Hensley[1] and Elizabeth Moore[2]

[1]Jet Propulsion Laboratory
California Institute of Technology
4800 oak Grove Drive
Pasadena, California 91109

University of London,
School of Oriental and Asian Studies,
Art and Archaeology Department

Abstract

During last year's AIRSAR Pacific Rim Deployment, data were collected over Angkor in Cambodia. The temples of Angkor dote the city to the 9th-13th century AD, but little is known of its prehistoric habitation. A related area of archaeological debate has been the origin, spiritual meaning and usc of the hydraulic constructions in the urban zone. The high resolution, multi-channel capability of AIRSAR, together with the unprecedentedly accurate topography provided by TOPSAR, offer identification and delineation of these features. In this paper, wc present results from our analysis of the AIRSAR/TOPSAR data obtained over Angkor. Some questions posed before the flights have been answered. The ability to view the landscape in the multiple modes made possible by AIRSAR has also generated new hypotheses on the development of Angkor. The potential to radically improve existing maps will assist archaeological investigation, and also inform tourism and agricultural development plans for the region.

1. INTRODUCTION

Angkor, meaning 'city', is located near the present town of Siem Reap in northern Cambodia, South of Angkor and Siem Reap is the Tonic Sap lake, one of tbc natural wonders of Southeast Asia. The Tonic Sap serves as a relief valve for the Mekong River during the May-October monsoon season, when it doubles in area. This seasonal inundation brings an abundance of fish, the main protein in the local diet. The receding floodwaters are captured by dikes north of the lakeshore, supplying a reliable source to begin the year's wet rice cultivation. The Tonic Sap is a striking feature of the Siem Reap floodplain, and a major factor in settlement of the region. It, along with centrally controlled irrigation and Hindu cosmology have been used to explain the urban phenomenon wc call Angkor. However, it was water to north of the city that was exploited and controlled by the water management structures of Angkor. The manmade alterations included circular and rectilinear moats, canals, rectangular tanks, and dikes used in various ways as above ground catchment devices. These lie low on the flat terrain, stretching across the landscape, in contrast to the tall temple-mountains built to house the Hindu deities.

The rivers and streams used to create Angkor had been known by many generations of villagers, settlements whose occupation did not cease when the first Hindu temple was built

(Moore, 1998). The tradition that flowered at Angkor incorporated Khmer and Indic concepts in the sacredness and usc of water, the architecture and the religion. Just as (heir hydraulic alterations spread out on the land, the Khmer define a horizontal dichotomy between village and forest. Animistic belief also exists within a horizontal natural-supernatural world structure, the spirits living on the same level as humans. once again, this horizontality contrasts the verticality of Indic cosmology in its tripartite division of the world into the heavens, the world of man, and the underworld (Ang Choulean, 1998).

The rectilinear features of Angkor are very striking in all forms of imagery of the area taken from above, including S1 R-C data. The *barays*, large artificial basins laid out inside dikes above ground level, are particularly notable, the largest stretching 8 kilometers cast-west (see the map in Figure 1). There is the network of feeder canals and moats, and of course, the remaining temples, such as the renowned Angkor Wat, set within a 200 meter wide moat. It is clear from decades of investigations by archaeologists, (see, for example, Groslier, 1979) that the Khmers controlled water on a large scale; they not only built moats and reservoirs, but diverted and canalized rivers.

Prior to acquiring the AIRSAR/TOPSAR data, data from SIR-C had been used to study the Angkor site. One of the authors had studied the site using World War 11 British and post-war French aerial photographs (Moore, 1989). Others have used SPOT data and JERS- 1 data to attempt a better understanding of Angkor. The present study was focused on several questions raised by earlier work:

1. Are there some unique features of the local topography which explain the siting of Angkor on the Siem Reap floodplain?

2. AIRSAR data was acquired over very sparsely settled areas of northern Cambodia, close to the Thai border. This area is not covered by British or French aerial photographs, 1 :50,000 maps, or French temple inventories. How far to the northwest of Angkor can man-made alterations be seen?

3. How far north does the distribution of circular mounds, such as Lovea, extend?

4. 1s there evidence for vestigial earthworks at circular sites northwest of Angkor linking them morphologically to known prehistoric mounds in Northeast Thailand?

5. Can water control features be accurately identified and separated from natural drainage features?

6. Can existing distribution maps of temple or *wat* sites be updated and improved upon?

In this paper, the first results of our analysis of the AI RSAR/TOPSAR data over Angkor arc presented.

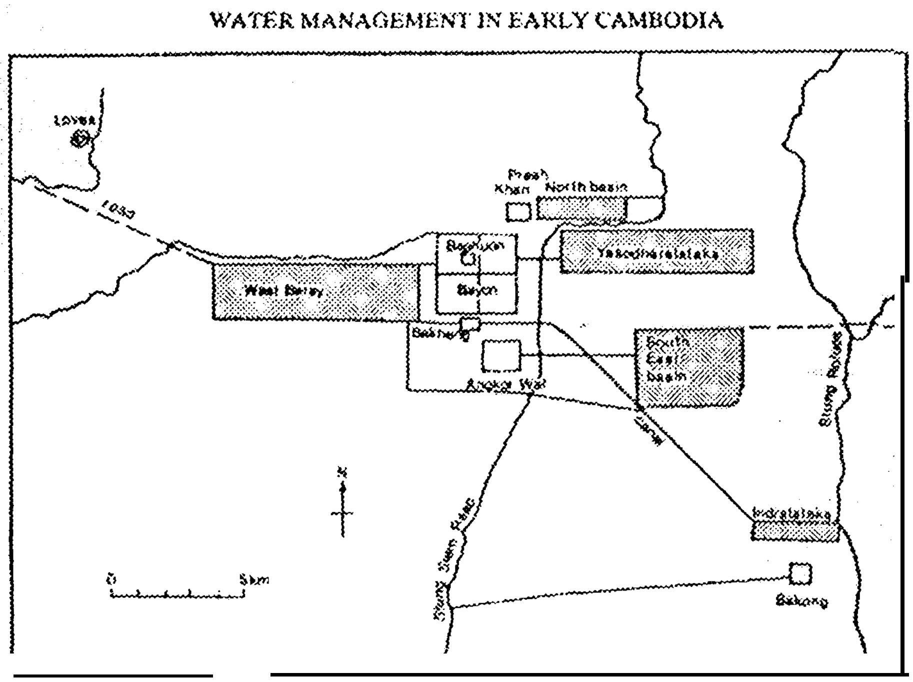

Figure 1: The city of Angkor and its surroundings, showing the large, rectangular barays and Lovea to the West

2. THE DATA

The NASA/JPL TOPSAR instrument flown on board a DC-8 aircraft can be used to generate very accurate high resolution topographic maps and imagery. This is especiall y important for areas such as Angkor where relief on a very small height scale (a few tens of meters), can control the flow of water over large areas of ground. Radar interferometry should work very well in such areas, allowing small-scale height variations to be mapped with high accuracy. The Angkor region data were collected during the 1996 PacRim Deployment and processed to ground pixel postings of 5 and 10 meters. The height accuracy for the Angkor elevation data varies between 0.5 to 2m depending on where the elevation is measured. Previous maps of the area have contours at only 5-10 m intervals. The TOPSAR instrument also measures C-Band backscatter and this is used to produce corresponding images to the elevation data.

Slightly inundated old paddies with rice stubble tend to appear as bright or white regions in the C-band (6 cm) radar imagery, while wind-roughened water or low growing vegetation may appear as smooth gray areas. Tree canopies appear as rougher gray areas, which can be identified using texture measures. Roads or calm water which are smooth surfaces appear black in the radar images because only a small amount of energy is returned to the radar.

As has been noted in studies conducted in other areas, L-Band radar data responds to medium-]cvc] vegetation, such as crops and shrubs It is usually possible to separate tree-covered areas from areas with medium or low vegetation cover at L-Band, but not to separate different biomass levels in mature forests.

Tree-trunks and larger branches tend to show up well at P-band (68 cm). P-Band radar backscatter data has good sensitivity to woody biomass up to 400 tons per hectare, according to (e.g. Le Toan et al, 1992). P-band data was not available from NASA's earlier SIR-C missions (1994) because SIR-C had just C, L and X-band radars. Vestigial earthworks around some of the circular mounds northwest of Angkor show up well at P-band due to sparse woody vegetation, perhaps the trunks of trees. Two circular sites, Phum Pongro and Phum Romiet, display remnant earthworks at P-Band when the HHVV ratio described below is placed in a three image composite, along with PHH and PVV.

The P-band data is fully polarimetric and one way to display this data is as a composite of three images representing different polarizations or polarization combinations. Each image or channel is assigned one of three colors (red, blue and green). Comparison of L-Band and P-Band has allowed us to differentiate current from disused areas of rice cultivation. Combined with the C-Band return, we thus have the potential to generate a map of present and past cultivation practice in the Angkor region.

The ratio between the HH and VV backscatter helps to distinguish between moist versus drier areas, an example of which is distinguishing what appear to be old moats from drier earthworks. Another way to display the P-Band (and L-Band) polarimetric data is as phase difference or correlation coefficients between the polarization channels, which tends to help in separating scattering behavior such as returns from double-bounce reflections and those from rough surfaces of vegetation canopies. It is also possible to estimate the contributions from different scattering mechanisms, for example as discussed in (Freeman and Durden, 1992). The scattering mechanisms have been useful in a preliminary study examining both circular prehistoric and rectilinear historic features at Angkor (Moore and Freeman 1998).

Figure 2 shows three of the images generated during the deployment. They are a C-Band VV image, an L-Band total power image and a P-Band total power image (total power here refers to the sum of the backscatter from all four polarizations, HH, HV, VH and VV). The site imaged is one that has been studied from aerial photographs and in situ by one of us (Moore, 1989), and which lies West of the city of Angkor. On the left side the image contains a large rectangular moat and a rectangular tank below it, next to an old Khmer road which runs from across the image from top to bottom. This is the site of the Khmer temple of Banteay Sras, dated around 1200 A.D.

On the right-hand side of the image is a roughly circular village, with a circular earthwork around it. This site is known as Lovea, which was established in pre-Khmer times, probably before 500 A.D. Ground survey at Lovea, and three other circular mounds to the north has brought to light a unique configuration of spirit posts not found at other Khmer villages. A single post, or group of five, is planted at the mound's center. The post or posts are non-anthropomorphic, and seem to represent notions of the earth as a living spirit, for they are distinct from shrines to the territorial spirits of the village, the *neak ta* (Ang Choulean, 1997).

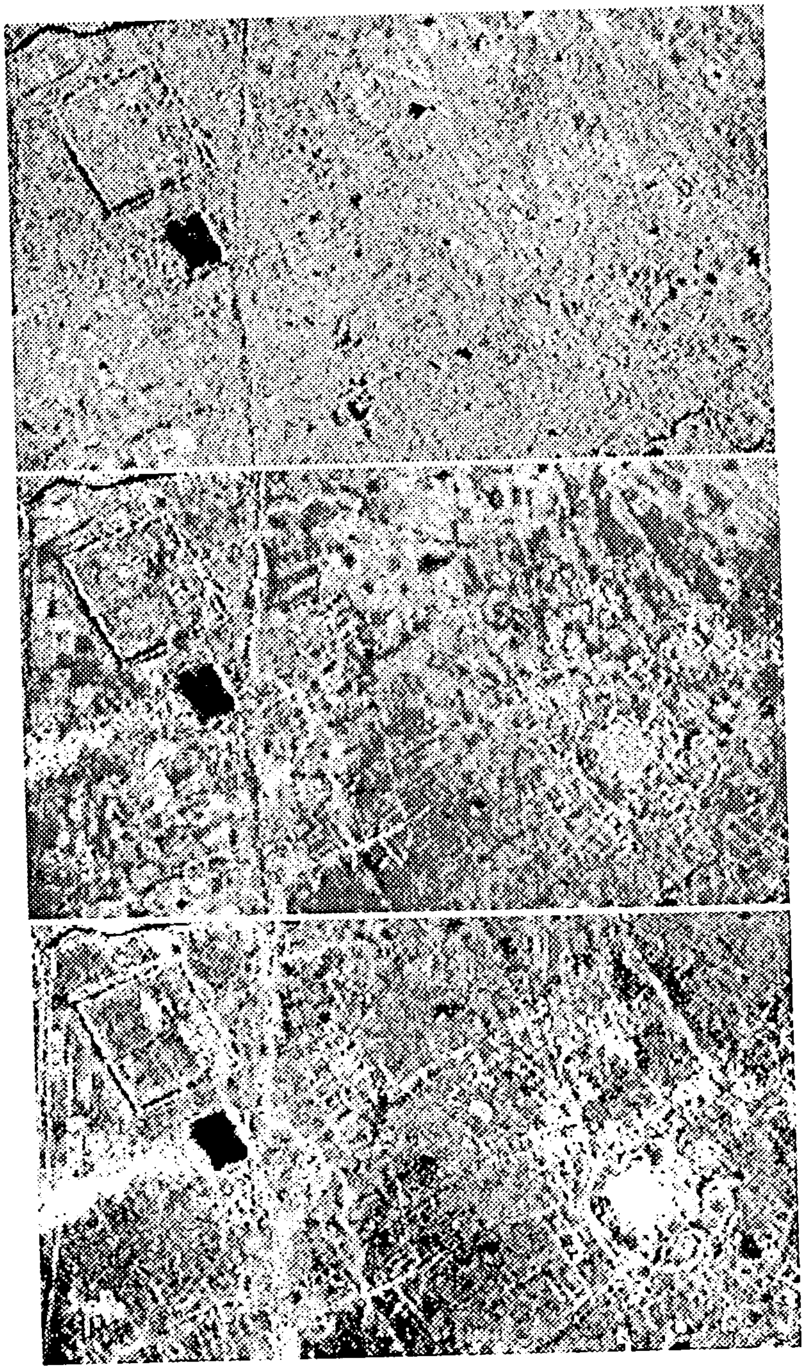

Figure 2: C-Band VV (top), L-Band Total Power (middle) and P-Band Total Power (bottom) AIRSAR images of Banteay Sras and Lovea, which lie -20 km North-West of Angkor. Banteay Srah (12th C.) is the pair of rectilinear Khmer-built features visible on the left, Lovea (pre-500 A. D.) is the circular settlement visible on the right

As discussed above, the differences between these three images can primarily be attributed to the differing radar back.scatter versus wavelength in each case. In the C-Band image, some rice paddies appear white, some open water areas appear dark, but the remainder of the image is a fairly uniform gray level. At L-Band, different levels of vegetation give rise to some variation amongst the fields, and the tree-covered areas tend to stand out. At P-Band, only the areas with tree or shrub cover appear bright.

Figure 3 shows one representation of the topographic data provided by TOPSAR which wc have found useful. It is a shaded relief map generated by simulating the illumination of the topographic data from a gi ven d irect ion. Elevated feature.s within the scene tend to stand out very well in these shade relief maps. For example, the dikes used to construct the moat around Banteay Sras are clearly visible, as are the raised walls of the water storage tank, the raised mound at Lovea, and the raised circular earthwork around it. The elevated road can also be seen clearly on the original. Just north, i.e. to the right, of the road is a small temple marking the west edge of a *baray* south of Lovea (not visi ble on this image). This feature is also visible in the P-Band image.

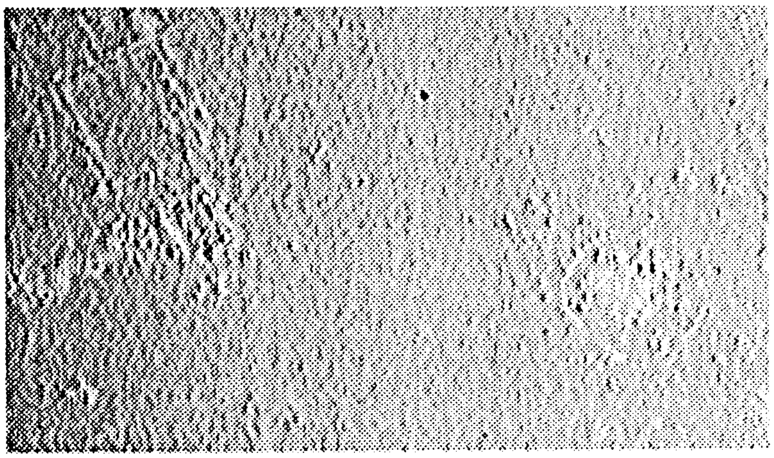

Figure 3: Shaded Relief image from TOPSAR data of Banteay Sras and Lovea, which lie ~20 km North-West of Angkor. Banteay Srah (12th C.) is the pair of rectilinear Khmer-built features visible on the left, Lovea (pre-500 A. D.) is the circular settlement visible on the right

Since TOPSAR is a C-Band instrument, it is expected that for relatively dense vegetation canopies, the heights measured cm-respond to somewhere close m the top of the canopy. This means that the largest factor in the relief seen in Figure 3 is probably the trees which populate the elevated roads and other earthworks, i.e. the measurements cm-respond to the tops of the trees, or c1osc to them. This may cause a problem in interpretation of the topographic data. Thus far, in our study of the data, we have found that trees in the flood plain of the Tonic Sap, are only located on raised earthworks, or on naturally elevated mounds (of which there are few). We speculate that this is due to the presence of at least a meter or so of relatively dry soil, above the local water table, in which the trees can establish their root systems.

Given the accuracy of the height maps generated by TOPSAR (0.5 to 2m), wc can begin to see natural drainage features which are depressions onl y a meter or so deep over a kilometer wide extent. Wc can also scc clearly the earthworks used to construct the large Barays at Angkor, and other, Icss-well-mapped earthworks. The thematic images generated by overlaying C-, L- and P-Band backscatter images in color allow better separation of field boundaries, and identification of tree-covered areas, for example.

One result that can be shown clearly in gray-scale images is the possible discovery of a temple or Wat, located to the North of Angkor, which does not appear on existing maps of the area. This is shown in Figure 4. The temple, a nearby tank for water storage, and the surrounding earthworks, clearly show up on the shaded relief and P-Band images, and to a lesser extent on the L-Band image. It is difficult to see the same features in the C-Band image.

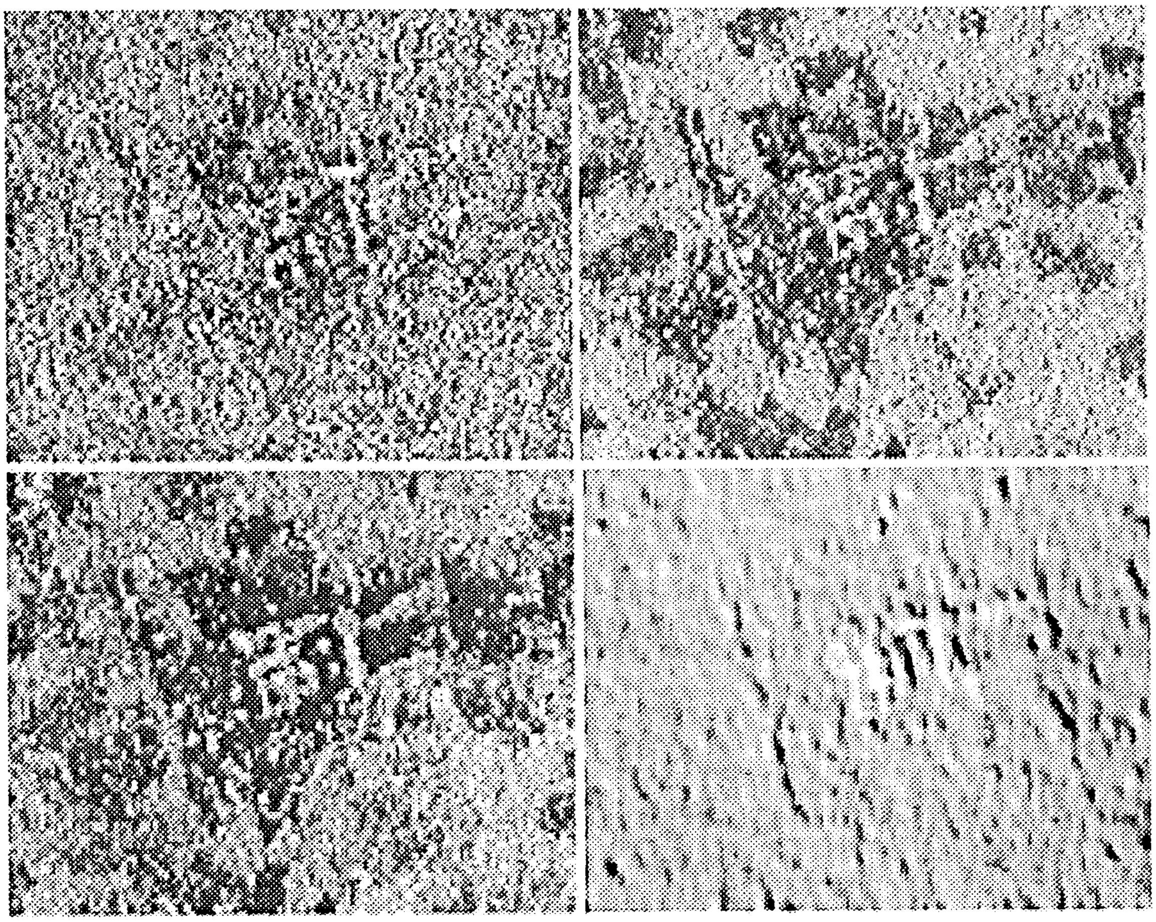

Figure 4: C-Band VV (top left), L-Band Total Power (top right), P-Band Total Power (bottom left) and shaded relief (bottom right) AIRSAR images of a temple or Wat located NNW of Angkor. Temple is not marked on existing maps of the area.

3. ANGKOR IN THE 10th CENTURY AD

3.1. The Old Khmer Road

A 30 meter wide earthen dike stretches for more than 10 kilometers, covering the distance between the 9th and 10th century AD capitals of Angkor. The road begins on the northwest corner of an aboveground reservoir, the Indratataka *baray* (3200 x 750 meters), and ends in the 10-13th century urban zone. Both the road and the *baray* can be seen in the map in Figure 1. The Indratataka is located near the modern town of Roluos, the late 9th century city of Hariharalaya. The *baray* is the earliest known structure of this type. Three *baray* were built in the following centuries: the early 10th century East Baray (7120 x 1700 m), the 11-12th century West Baray (8000 x 2100m), and the late 12th century North Baray (3400 x 800m). Although varying in size, all are approximately four times longer than they are wide.

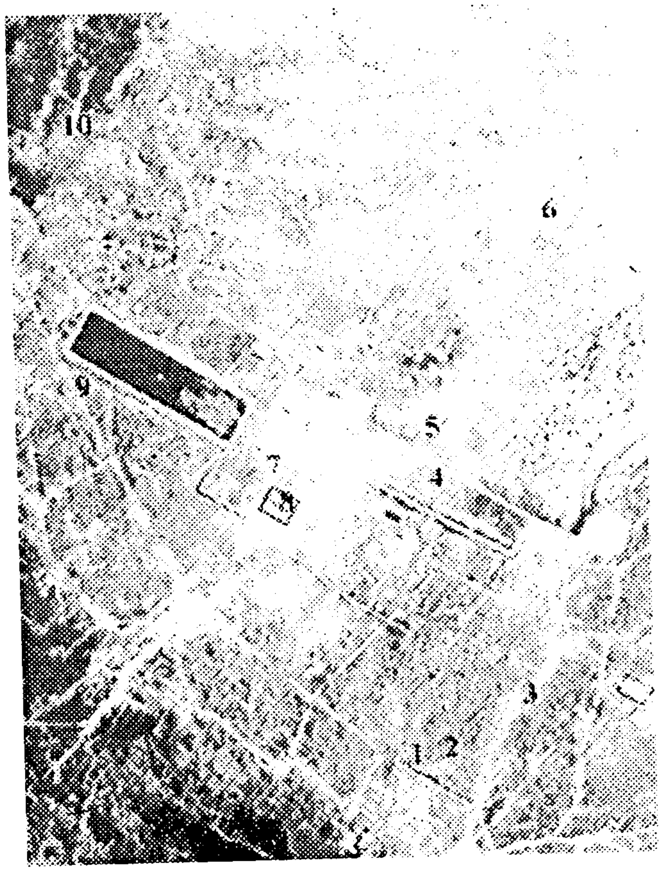

Figure 5. SIR-C image of the Angkor plain showing some of the places mentioned in the text. 1. Indratataka Baray, Hariharalaya, Roluos; 2. Lolei; 3. Roluos River; 4. East Baray; 5. North Baray; 6. Bam Penh Reach; 7. Phnom Bakheng; 8. Angkor Wat; 9. West Baray; 10. Puok Valley

As it links the old and new centers of power, the Old Khmer Road is reasonably dated to the late 9th century. When looked at in the context of the topography, the road appears to have played a strategic role in this move, as a transport, water management and agricultural construction. Both the S1 R-C and Al RSAR cover have been useful in relating the Old Road to other dikes, the East Baray, and in hypotheses about the 10th century hydrology of Angkor.

Contemporary inscriptions confirm that King Yasovarman I erected temples at both the old and ncw capitals, and was also responsible for the construction of the East Baray. He thus marked control of the territory and the river at Roluos, while extending his domain to the northwest with the Old Road, the temples and the East Baray at Angkor.

On 1:50,000" maps, the Old Road dots go 'uphill', but marginally, from about 11 meters at the corner of the Indratataka to 19 meters around the 10th century temple of Prasat Kravan. Some authors terminate the dike at Phnom Bakheng, a 99m hill at the center of the ncw capita]. Others extend it northwest to meet an cast-west road into the Royal Palace, a "triumphal way" (Jacques 1997:78). The dike is described as a road, with no reference to water capture (Groslier 1979: 174).

A definitive answer has been difficult to resolve as clear evidence for whether the dike stops at, or just past the road going from the west entrance of Angkor Wat and curving to the northeast, past Prasat Kravan. As this road dates to the early 20th century French period, it is presumed that the Old Road originally continued into central Angkor. There is some evidence on the radar topography and the PtpLtpCvv image that the road turned west, perhaps curving around a rectangular feature.

3.2 Paleohydrology

Before the 10th c. construction of the East Baray to the north, there were presumably many streams through the Kravan area. The radar topography and polarimetric images suggest that the Old Khmer Road may have cut across and diverted old courses of the Siem Reap River. The images reveal several possible water channels in the Kravan area. The river courses appear to have wc]l-defined V-shaped channels too wide to be man-made. Engineers would make usc of the natural features of the terrain wherever they could, so they may have been subsequently utilized as canals.

The evidence from the radar topography suggests these flowed north-south. The Roluos River flows north-south, as dots the Stung Siem Reap north of the East Baray. However, this portion of the Stung Siem Reap is di verted by a barrage at Bam Penh Reach, 10 km north of the East Baray.[1] This is a ponded zone, perhaps indicative of former river courses. Traditionally a single original course of the Siem Reap is postulated, flowing NE-SW to the Puok valley.

An E-W dike begins lkm south of the Angkor Wat moat, extending 10 km. Six km from the northwest comer of the Indratataka, the Old Khmer Road crosses this dike, bisecting a 90-degree angle made by a 3km N-S dike. These features show well in both the DEM and RGB images from the polarimetric data. The generally straight course of the E-W dike twists twice, once when it crosses the Stung Siem Reap, and again where the Old Khmer Road crosses. There was possibly an unfinished *baray* south of the East Baray; the 1 0km E-W dike, in its eastern portions, would have formed its south dike (Groslier 1979: 184). Thus water management has commonly been linked to this dike but not the Old Khmer Road (Garami & Kertai 1993:33).

The Old Khmer Road was not only a processional way, however. By diverting, or having the power to divert, the other large river in the area, the Siem Reap, the king did not abandon access and control of the city of Hariharâlaya at Roluos in the establishment of Yasodharapura at Angkor. He instead established hegemony over a second river system and cultivation zone. In this construction program, the East Baray may post-date the Old Khmer Road, or the two features may be an integrated construction.

3.3. Ancient cultivation

The L-band green on the radar RGB images reveal some evidence of former cultivation in areas which are now abandoned, in the Kravan area southeast of Angkor. Looking at the P- and C-Band (red and blue, respectively), the left-hand portion (southern) of the image appears to be mostly dead ground, a few rice paddies (which appear bright blue), but mostly abandoned. Adding the L-Band (green) reveals a patchwork of vegetation. These may be abandoned fields.

This suggests a larger temple zone than the immediate temple enclosure. The lack of temples in this area is notable. Prasat Kravan, with an inscription of 921 AD, coincides with the reigns of two of Yasovarman I's sons. It is also the date when Jayavarman IV establishes the new capital to the North, at Koh Ker (Clink Gargyar). It is not until the reign of Rajendravarman (944-68), that the center of power is returned m Angkor. During the Koh Ker interregnum, Kravan may have not only consecrated but defended the northwest end of the dike, part of a water control system for the rice fields 'downhill'. The water would reach the fields via the N-S watercourses.

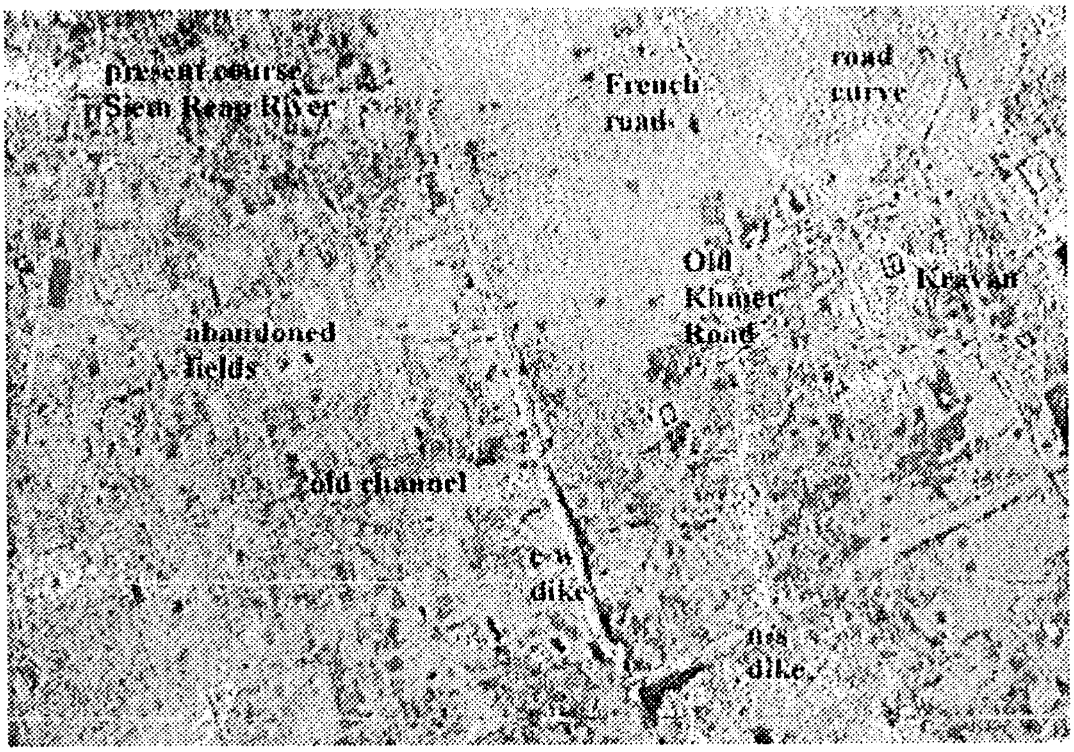

Figure 6: Kravan area composite of P-Band, L-Band, C-Band. The abandoned fields south of the E-W dike are L-Band. The Old Khmer Road is seen where it crosses the other dike. Prasat Kravan and the French colonial road are also visible.

3.4 'Moat' of the 10th century city

Features associated with the 10th century move of the capital from Hariharâlaya to Angkor include temples and water management structures. The king built his slate temple on the 99m hill of Phnom Bakheng, surrounding the foot of the hill with a moat (650 x 436 meters). He built a shrine commemorating his ancestors on an island in the middle of the earlier *baray* at Roluos, called Lolei (893AD). He constructed the East Baray (Moore 1977[forthcoming]). The 300-m wide outer moat of his city, Yasodharapura, is estimated to have been a 4-km square. If correct, it would have been both the first and the largest city at Angkor. [2] Only the south and west sectors of the moat are visible today. There is no evidence for the moat on the east side, and some authors suggest that the outer parallel dike was not constructed until the 11 th century when the existing dike became part of the east wall of the West Baray (Jacques 1997:78).

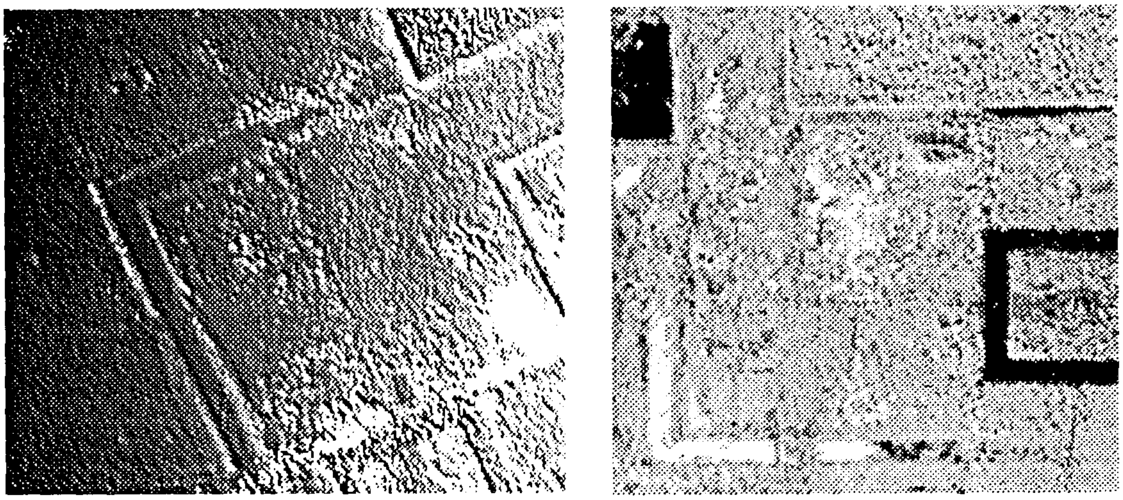

Figure 7. The moat around Phnom Bakheng, seen as a shaded relief image on the left and as a CVV amplitude image on the right.

Given the epigraphic evidence linking Yasovarman to the Lolei and Bakheng, it has always been presumed that the dike coming off the northwest corner of the Indratataka was his work. The radar topography has prompted investigation of the zone traversed by the Old Khmer Road, the paleohydrology, and its function as a water control device in ancient cultivation of an area which today has little habitation or paddy fields.

5. SUMMARY AND DISCUSSION

Recent research has led to unexpected discoveries and innovative interpretations of Angkor. We have been able to identify and assess natural and manmade water management features, and to image existing as well as unmapped temples. The radar imaging has provided insight into the way in which the ancient Khmer both exploited and over-rode the slope of the floodplain the engineering of dams, canals, and barays. It has generated hypotheses on the presence of pre-Angkorean river courses in what was to become Angkor in the 9th - 13th century AD. We have been able to verify the presence of mound sites and alteration of the terrain far to the northwest of Angkor (to some 15 kilometers south of the Thai border). Different hydrological zones have been defined, helping to explain apparent occupational shifts in relation to the early mound sites in the Puok valley northwest of Angkor, the 9th century AD capital of Hariharalaya southeast of Angkor, and the succession of ritual centers at Angkor from the 1 [M-13th century AD.

Synthetic aperture radar (SAR) offers a new tool for the mapping of Angkor. This observation tool does not stand in isolation from optical imaging. It dots, however, provide a unique perspective of immense alteration of the terrain, particularly in the hydrology of the low-sloping floodplain, offers an excellent test case for the JPL/NASA AIRSAR instrument. The data from the 1996 airborne AIRSAR platform has complemented data gathered from the spaceborne SIR-C/X-SAR carried on the Space Shuttle Endeavour. The correction and expansion of previous maps has been possible through the spatial (5- 1(1 meters) and elevational (().5-2 meters) resol ution of i mages processed from the AIRSAR data. Data was acquired at different radar frequencies (68cm, 24cm, 6cm), with multiple polarizations (horizontal and vertical combinations). The TOPSAR instrument has allowed us to begin the mapping of Angkor in an unprecedented manner, interpreting its unique position on the floodplain. The project addresses underlying aims of reconstructing the prehistoric landscape of the Sicm Reap plain and the role of hydrological alternation in the urban evolution of Angkor.

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[1] The Bam Penh Reach diversion is some 10 kilometers north of the East Baray, and is often dated to the 11th century reign of Rajendravarman. Its artificial nature is reinforced by a contour line cm 1 :50,000 maps, some 3 kilometers north of the East Baray, which cuts directly across the streambed.

The present course of the Sicm Reap through Angkor, however, is often placed only in the 16th century. The break in the dike running from the northwest corner of the East Baray to the northeast corner of the moat around Angkor Them is also dated to the 16th century, with the possibility that there was already an opening which was enlarged.

The Spean Thma bridge, with 14 spans each one meter high and 2.5 meters wide, is on the cast side of Angkor Them. Its construction indicates that the river once was 5 meters higher than at present.

A further theory is that the present course, bet ween Angkor Them and the East Baray has always been the river course. This is countered by the argument that central Angkor is a high point of a terrace and never would have carried a riverbed (see Garami and Kertai.1 993: 26).

Both Barn Penh Reach and Phum Khlat were identified by onc of the authors as possible prehistoric sites in the ZEMP inventory (see Moore, E. 1993. Ancient Habitation on the Angkor Plain, report for UNESCO Zoning and Environmental Management Plan for Angkor).

[2] The moat is thought to have been at least 3 meters deep, and would have held some 15 million cubic feet of water. If, as presumed, the meal was fed from the East Baray, the amount of water in the baray would hove been considerably reduced. One hypothesis is that the moat water was drained via a canal visible at the southwest angle of the Bakheng moat. (Garami & Kertai 1993:36)